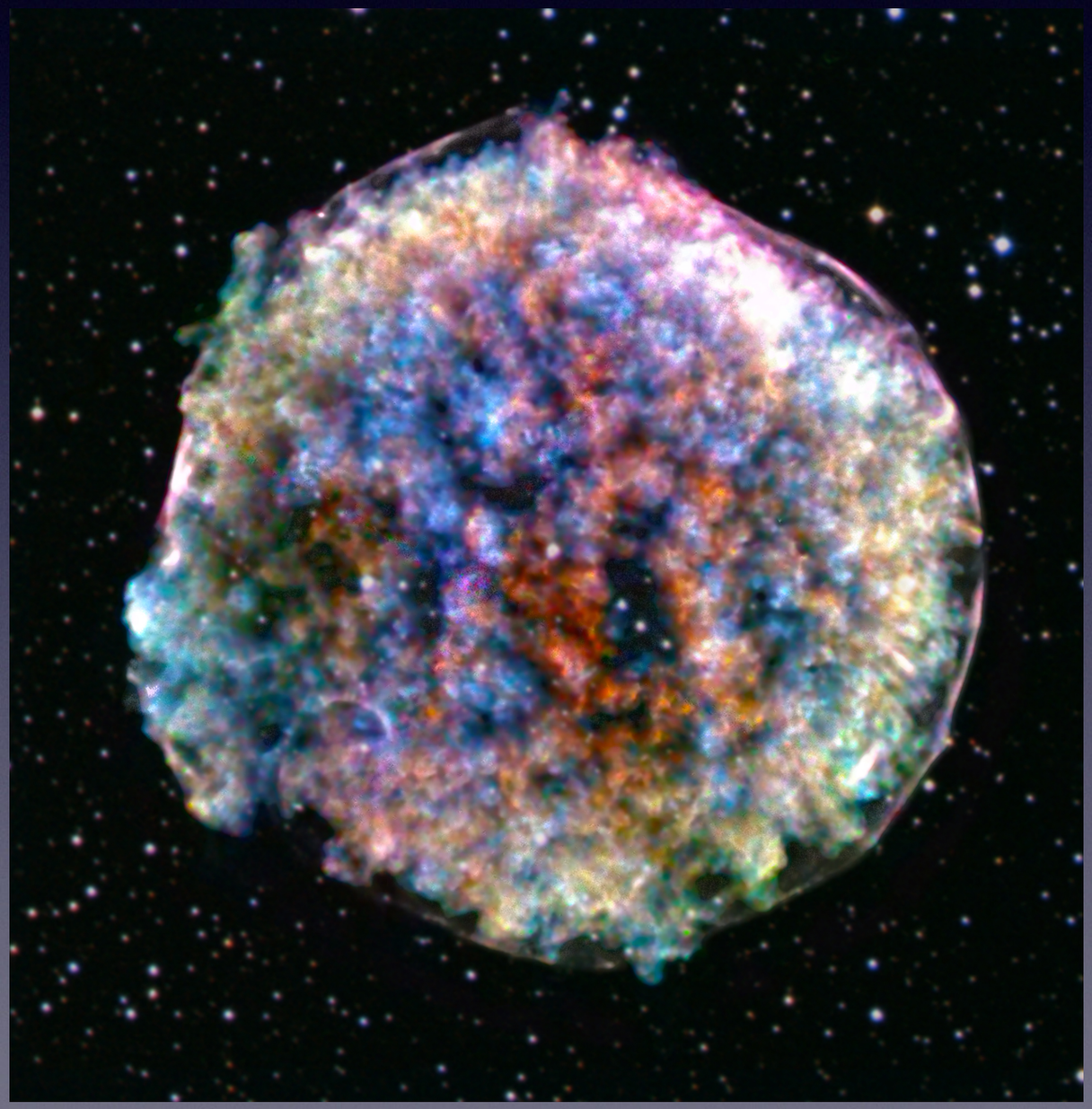
Two Decades of Evolution of Tycho's Supernova Remnant



Brian Williams
NASA GSFC

One slide on personal reflections on Chandra

My first science conference

Six Years of Science with Chandra
Dedicated to Leon Van Speybroeck

The third in a series, this meeting will highlight science results from the past six years of operation of the Chandra X-ray Observatory with emphasis on recent results. Contributions covering recent results from the XMM-Newton Observatory will also be presented.

2 - 4 November 2005

Royal Sonesta Hotel Boston
Cambridge, Massachusetts

The Symposium Proceedings are now online. Talks and posters are being added to the proceedings pages daily.

Send in your poster! If you presented a poster and have not yet submitted it for the proceedings, email sixyears@head.cfa.harvard.edu for instructions.

Download the Official Symposium Flyer
(high resolution PDF, 3.5 MB).

This version of the flyer includes the invited speakers and some of the science topics that will be discussed at the symposium.

Picture taken Monday

1 Chandra Lifetime = time to go from high-school student to “mid-career” scientist

Tycho Brahe

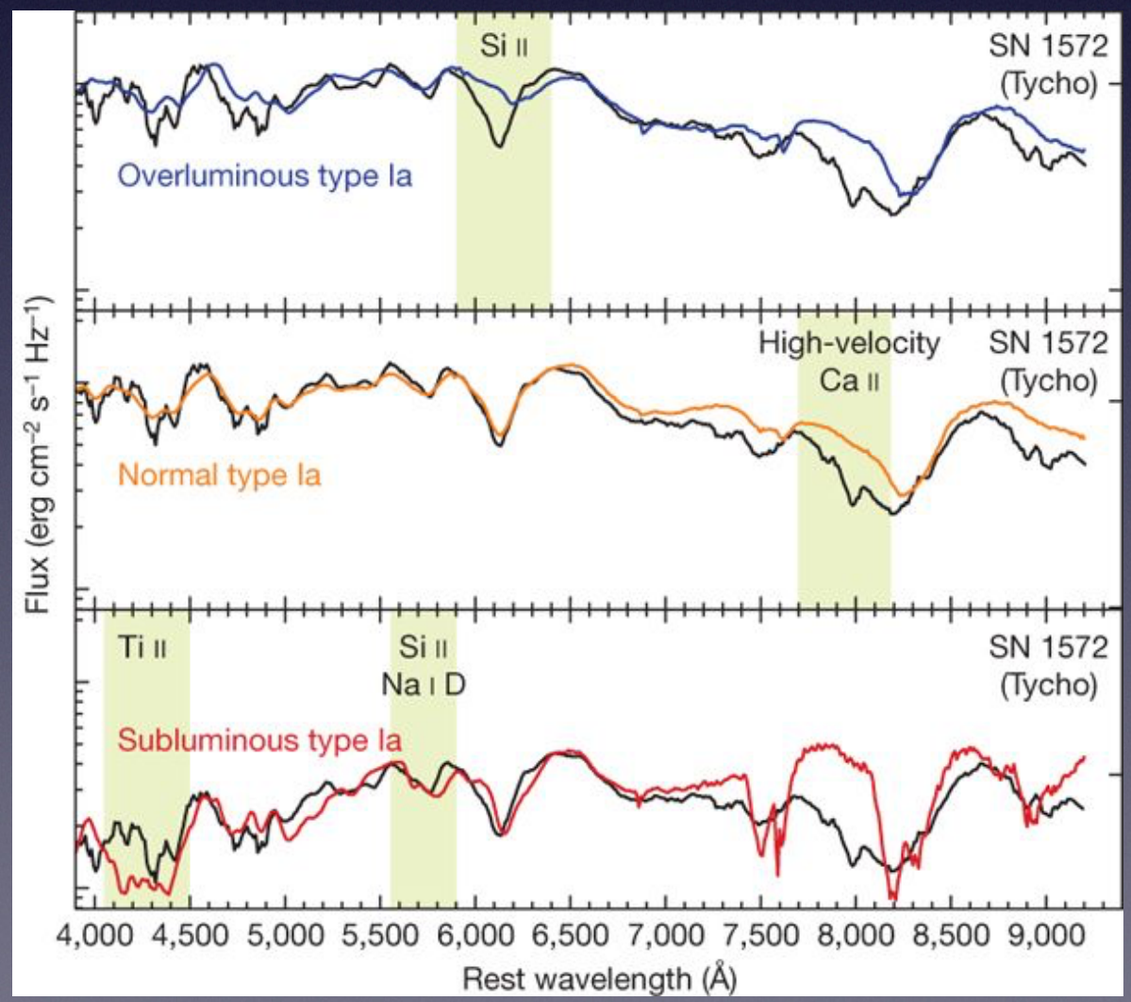
- Appeared in the sky in November 1572, stayed visible until early 1574
- Peak magnitude -4 (as bright as Venus)
- “helped to revise ancient models of the heavens and… challenged the Aristotelian dogma of the unchangeability of the realm of stars.” (h/t some Wikipedia editor)
- Baade 1945 re-analyzed Brahe’s observations and classified the supernova as “Type I”
- Light echoes discovered by Rest+ and Krause+ (2008) show it is consistent with a “normal Type Ia SN”

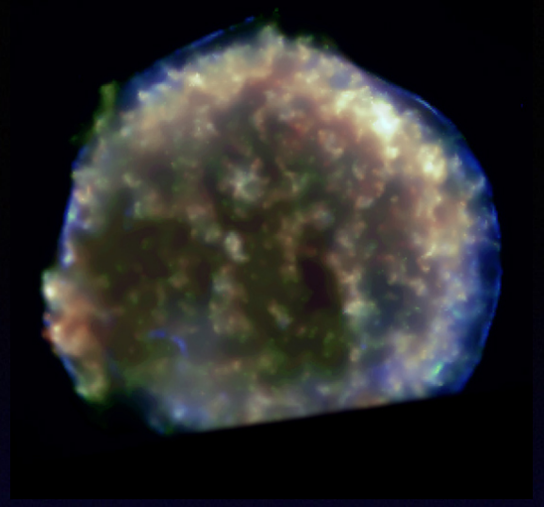
Tycho’s SNR

TABLE 2

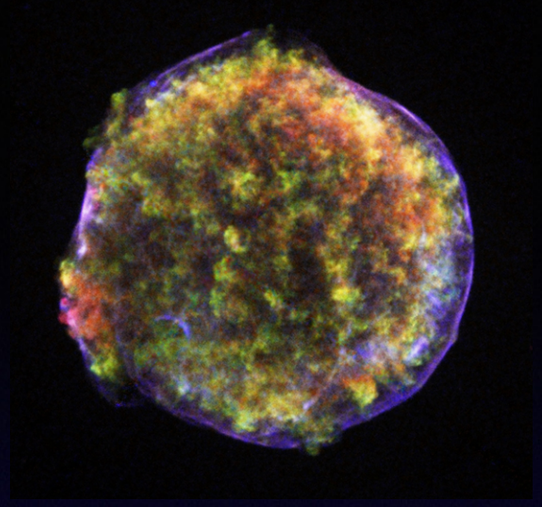
MAGNITUDES OF B CAS (1572)

Date (Tycho)	Adopted Mean Date (Julian)	Description	m_v	Phase
1572 Nov.	1572 Nov. 15	Almost as bright as Venus	−4.0	0d
Dec.	Dec. 15	About as bright as Jupiter	−2.4	30
1573 Jan.	1573 Jan. 15	A little fainter than Jupiter; considerably brighter than the brighter stars of first mag.	−1.4	61
Feb.–Mar.	Mar. 2	Equal to brighter stars of first mag.	+0.3	107
Apr.–May	May 1	Equal to stars of second mag.	+1.6	167
July–Aug.	Aug. 1	Equal to α, β, γ, δ Cas	+2.5	259
Oct.–Nov.	Nov. 1	Equal to stars of fourth mag.	+4.0	351
Nov.	Nov. 15	Equal to κ Cas	+4.2	365
1573 Dec.–1574 Jan.	1574 Jan. 1	Hardly exceeding stars of fifth mag.	+4.7	412
1574 Feb.	Feb. 15	Equal to stars of sixth mag.	+5.3	457
Mar.	Mar. 15	Invisible	.....	485

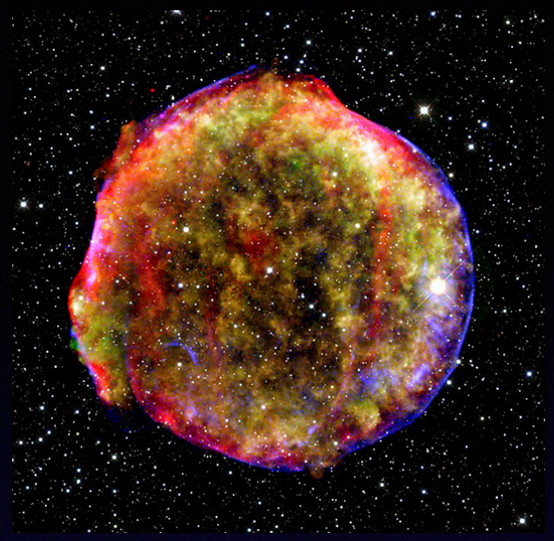




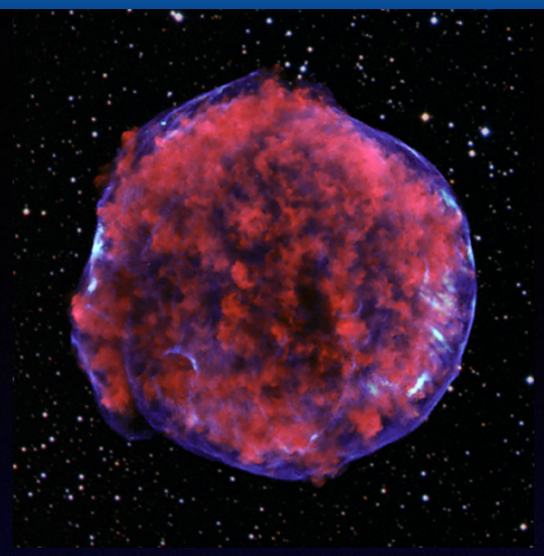
2002



2005

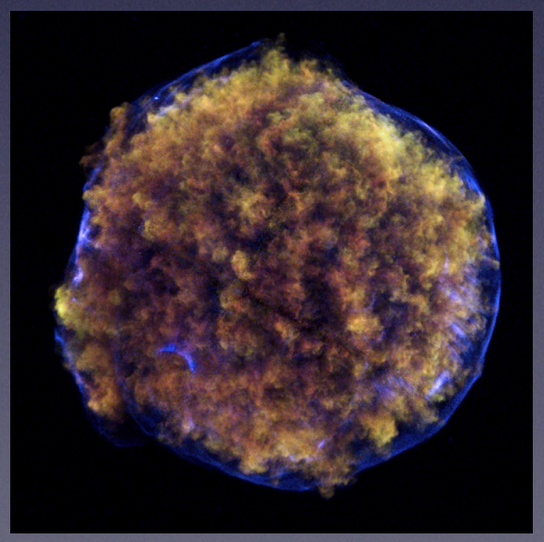


2009

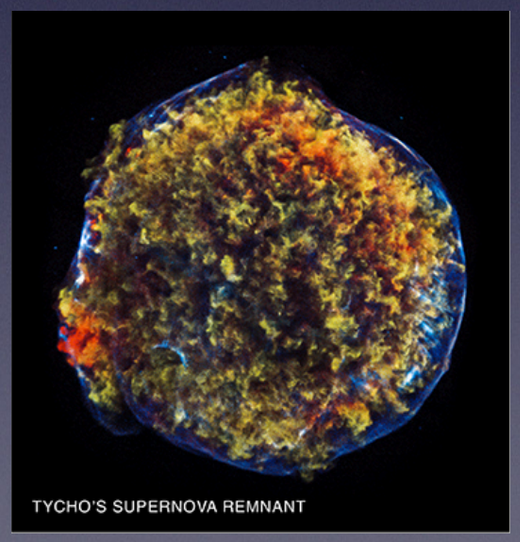


2011

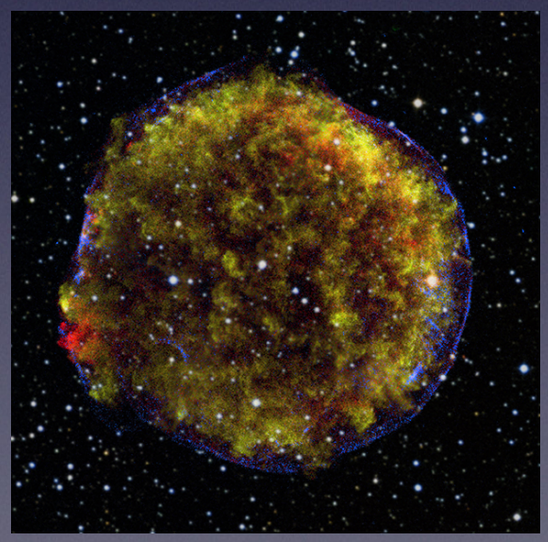
Chandra releases over the years



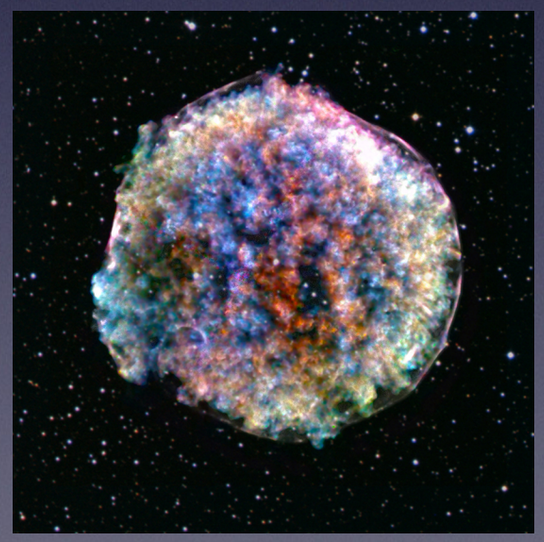
2011



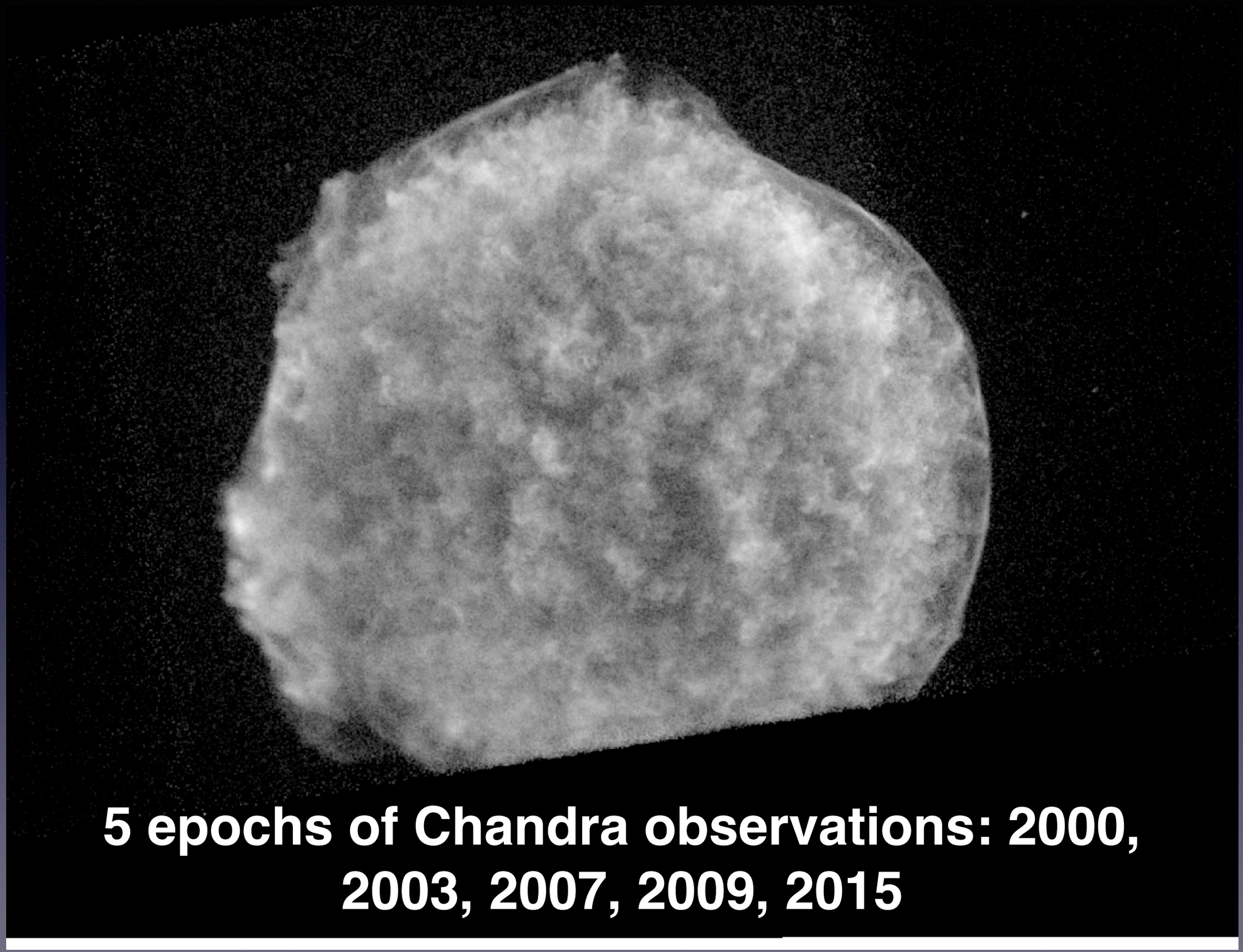
2014



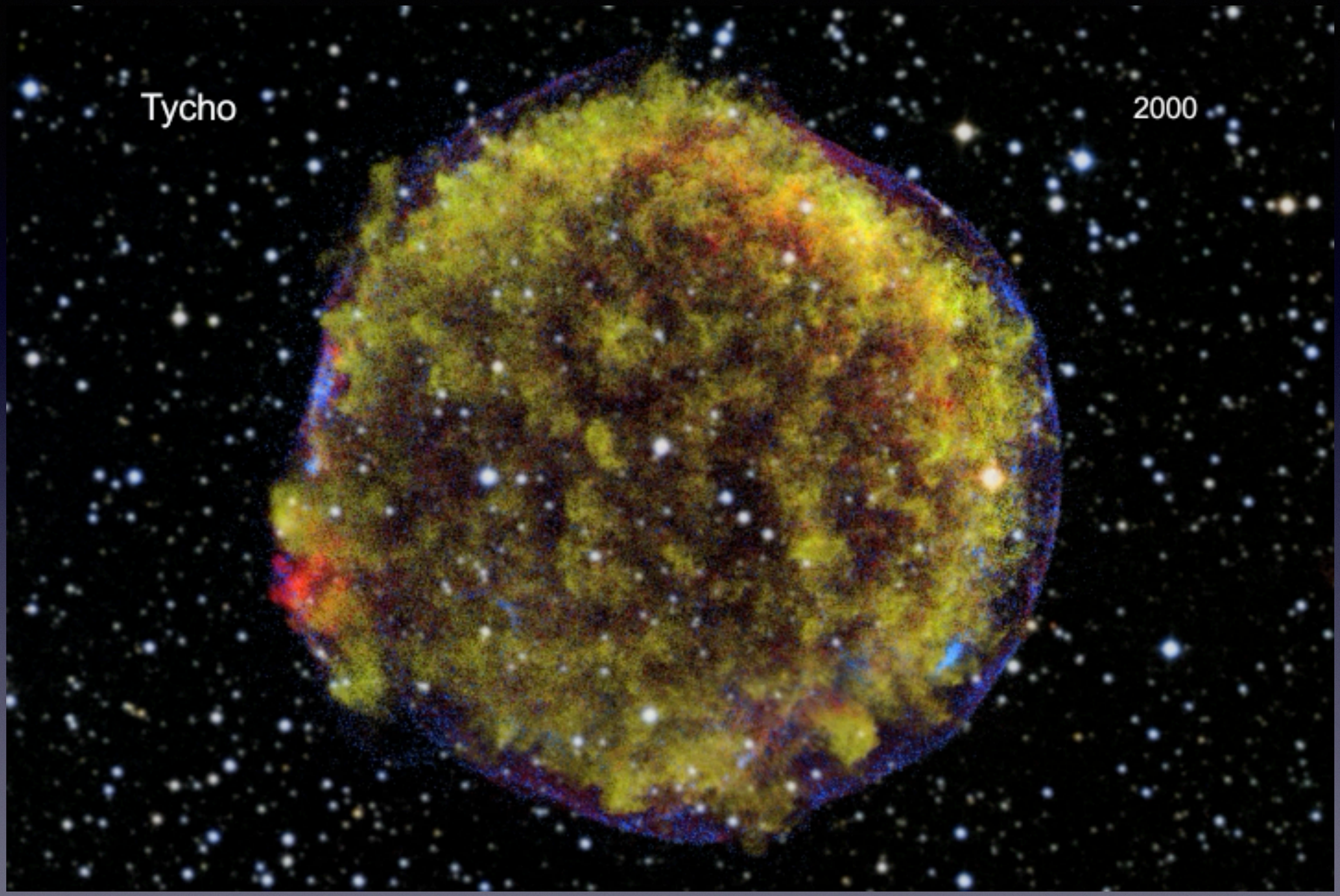
2016

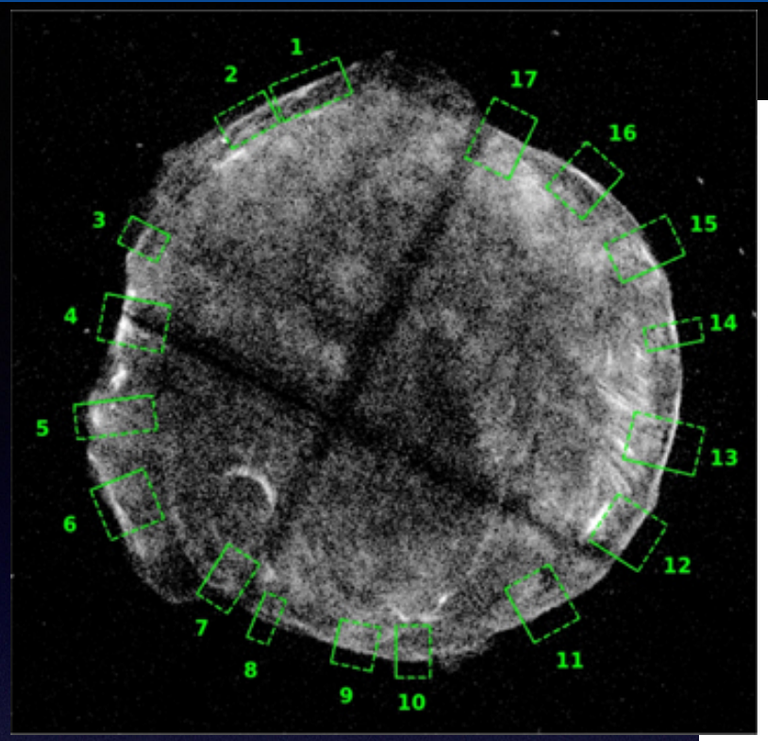


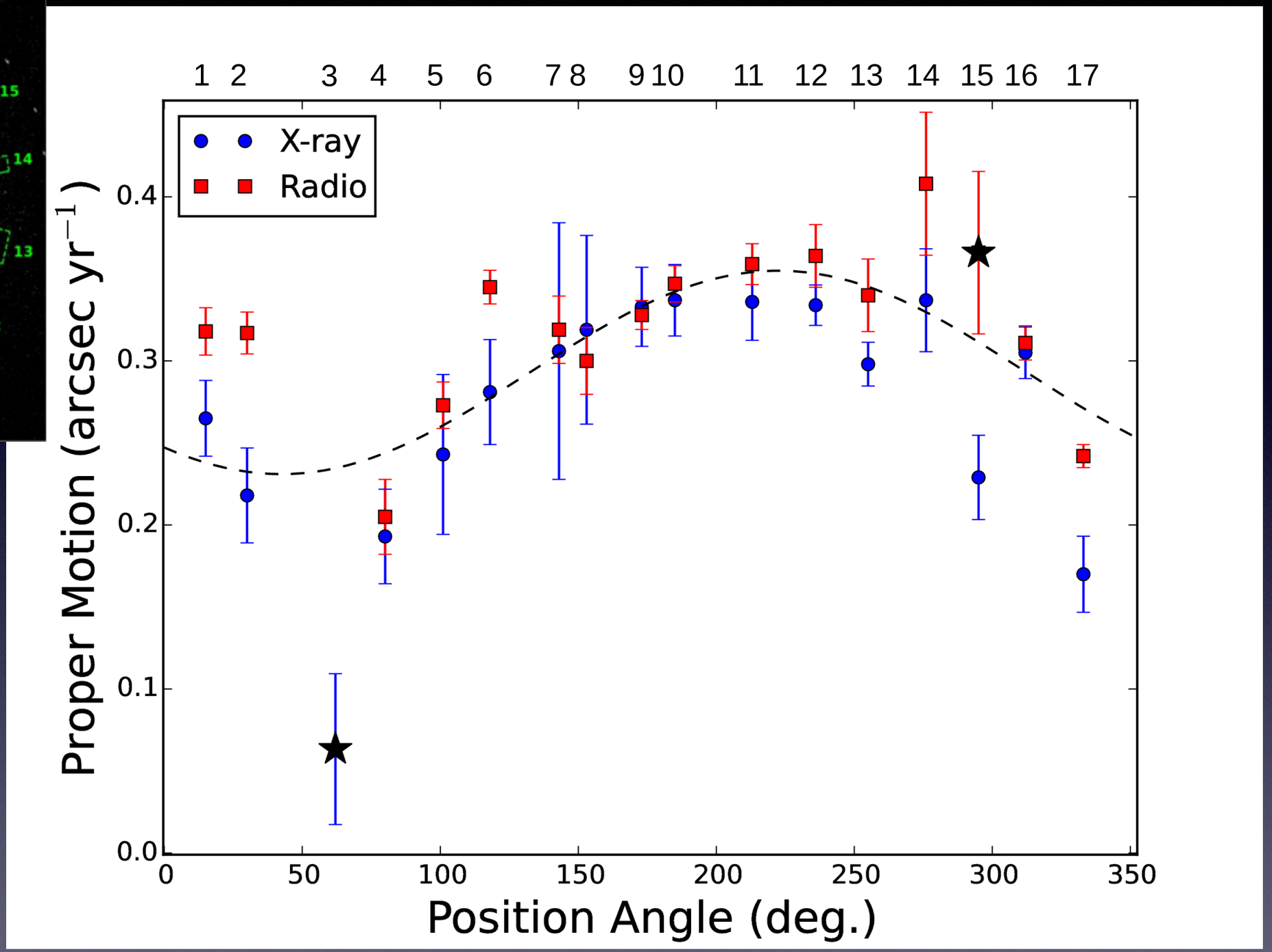
2019



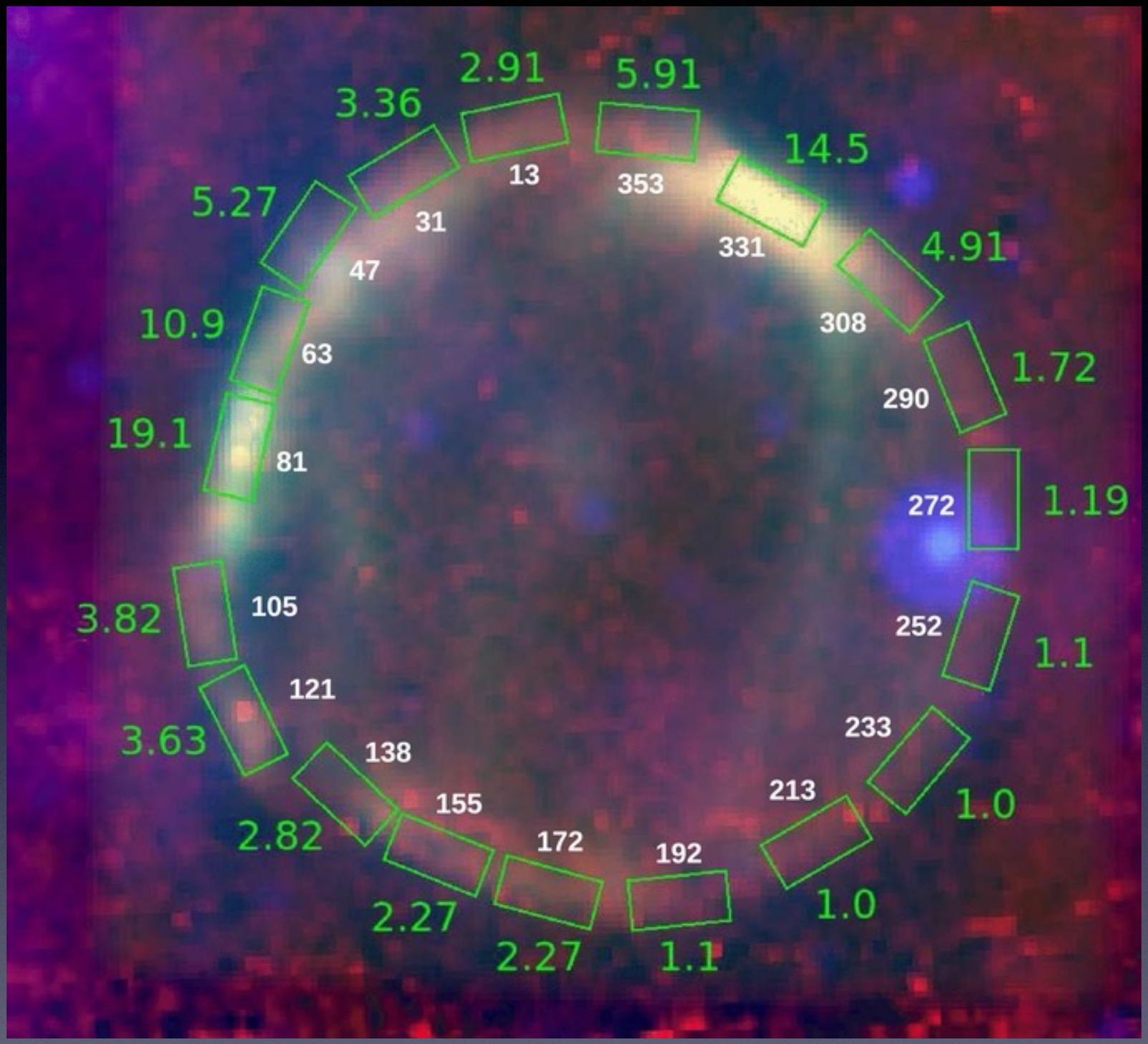
5 epochs of Chandra observations: 2000, 2003, 2007, 2009, 2015


Tycho
2000

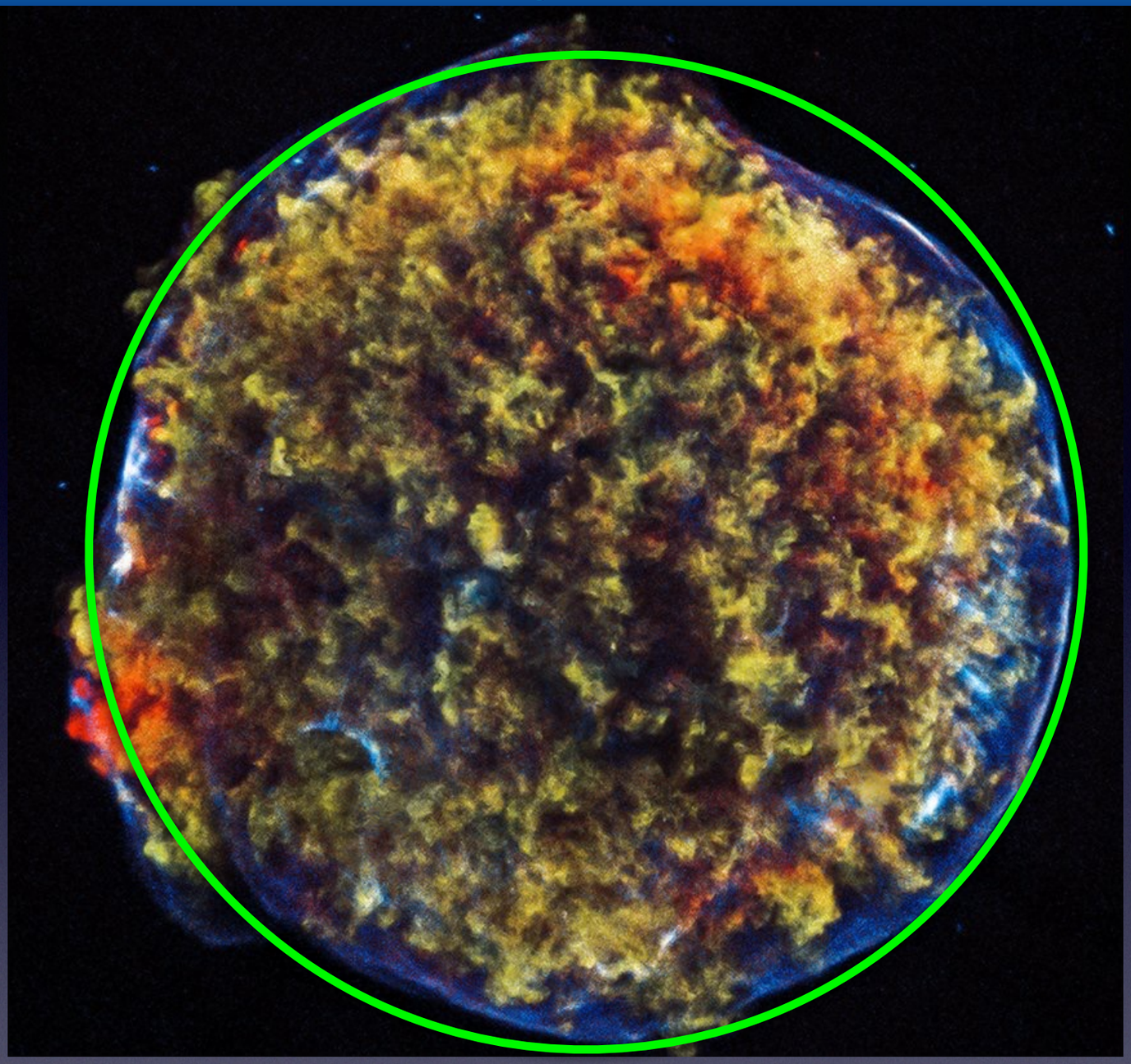




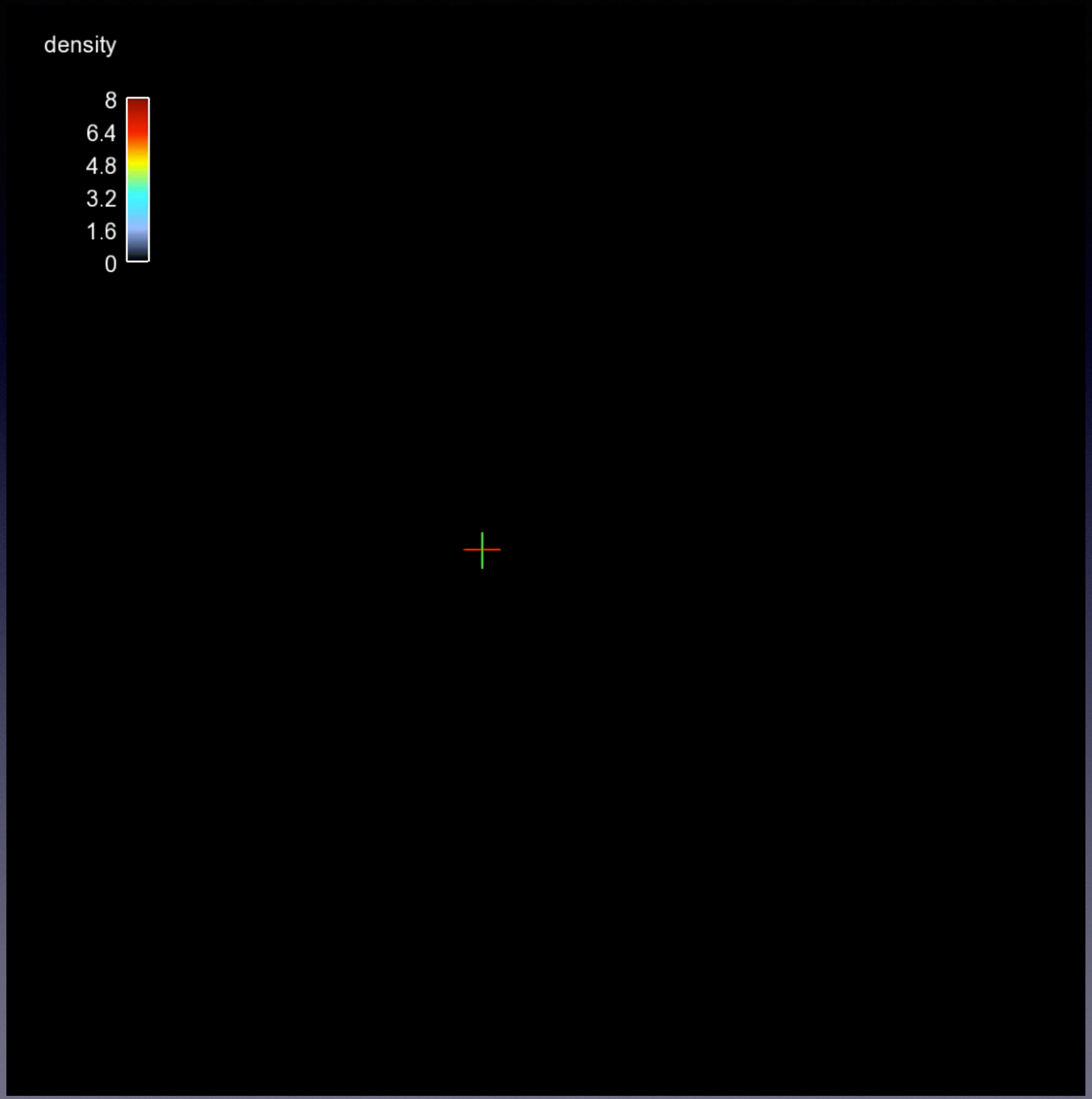
Plot from Williams et al. 2016, showing that expansion velocity varies by ~50% from one side to the other, consistent with earlier results from Katsuda et al. 2008



Williams+ 2013 measured densities of surrounding ISM, found evidence of density gradient. Pre-existing ISM structure? Molecular cloud (Lee+ 2004, Zhou+ 2014)?



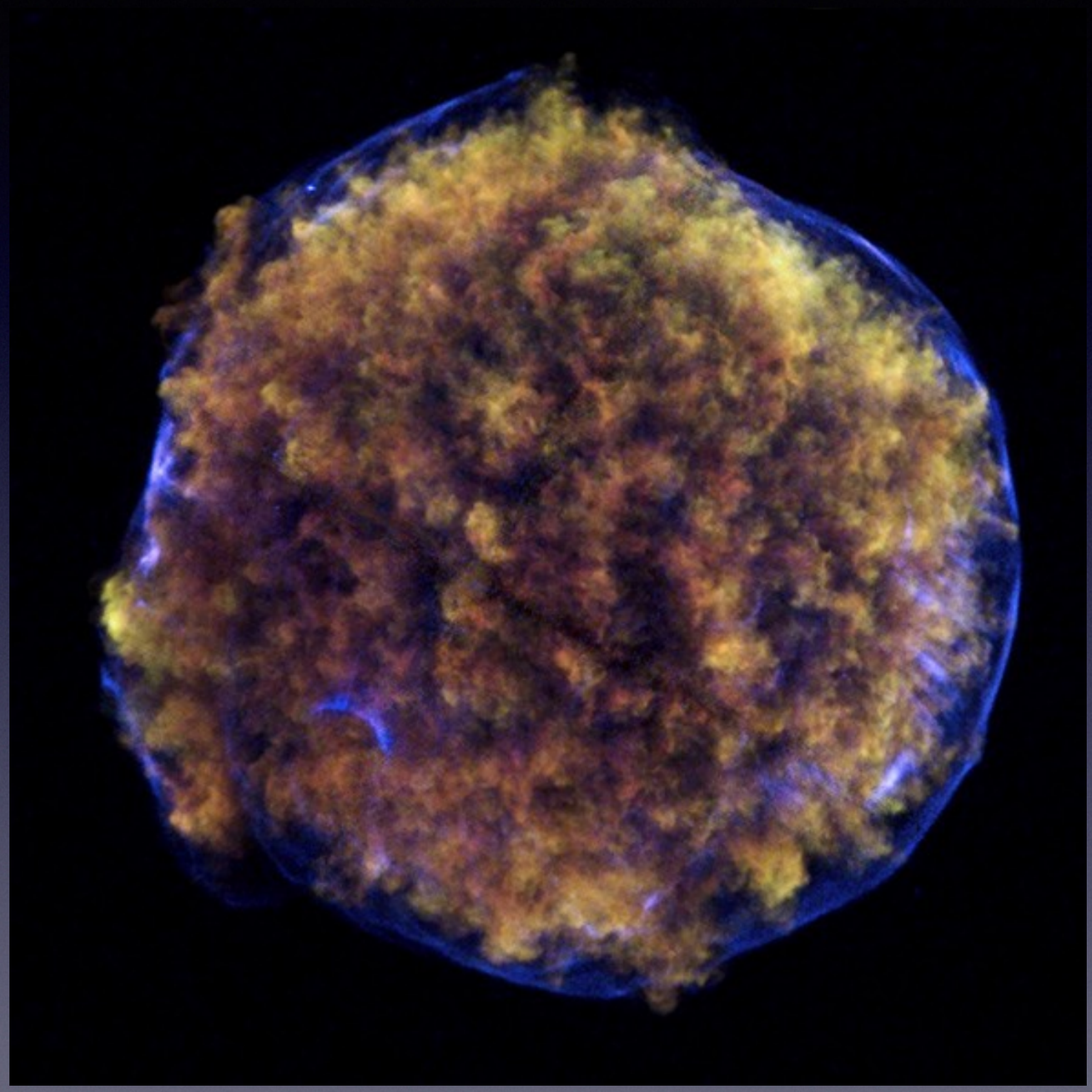
“But wait! Tycho is circular…”



Uniform explosion into a density gradient…

Still get a circle, but center of circle ≠ explosion site

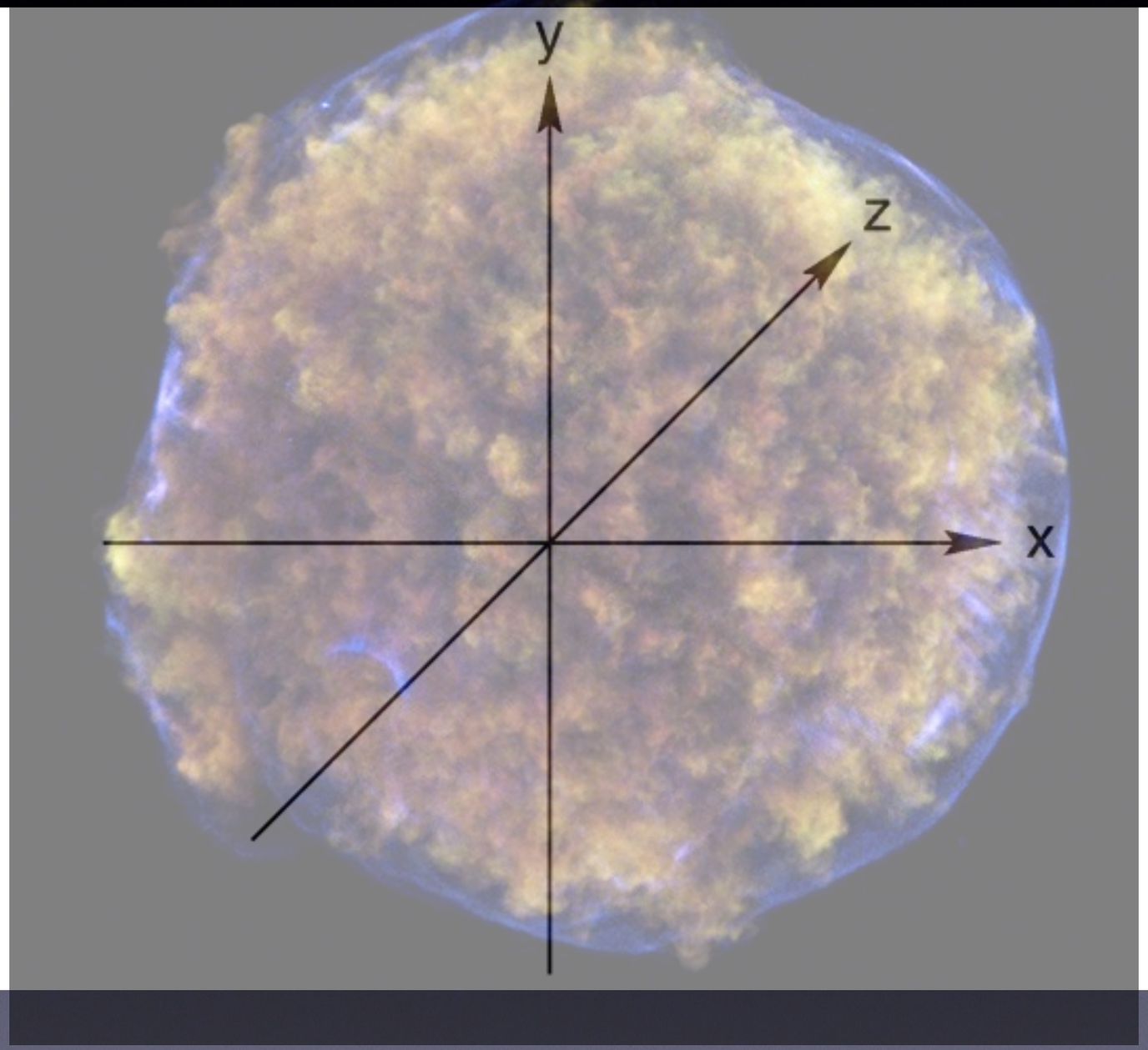
Dynamics of forward shock tells us about ISM. Dynamics of ejecta tell us about progenitor and explosion; see Williams+ 2017



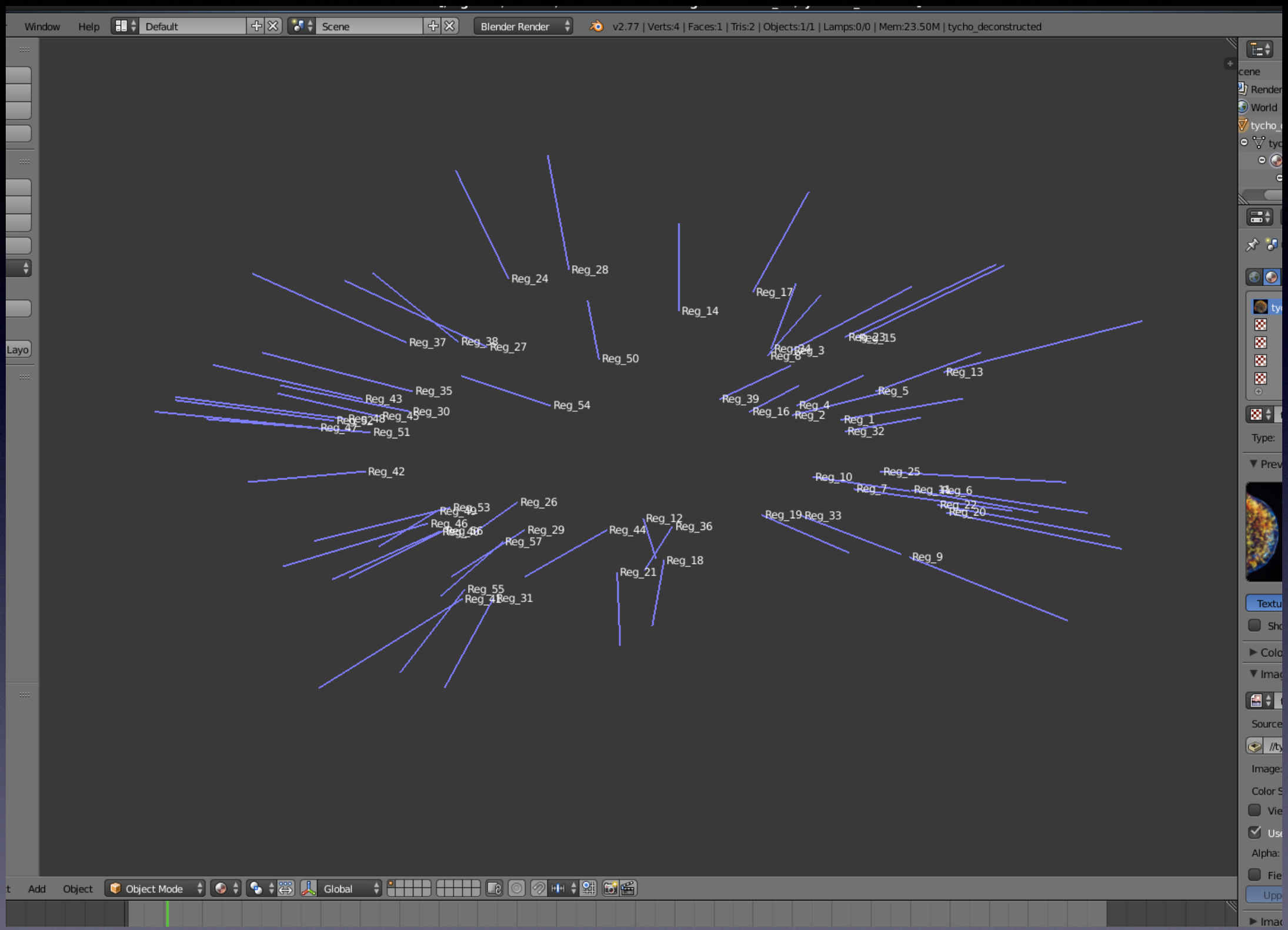
We can measure ejecta* velocities in 3D!

***ejecta = the fluffy stuff**

We can measure ejecta velocities in 3D!



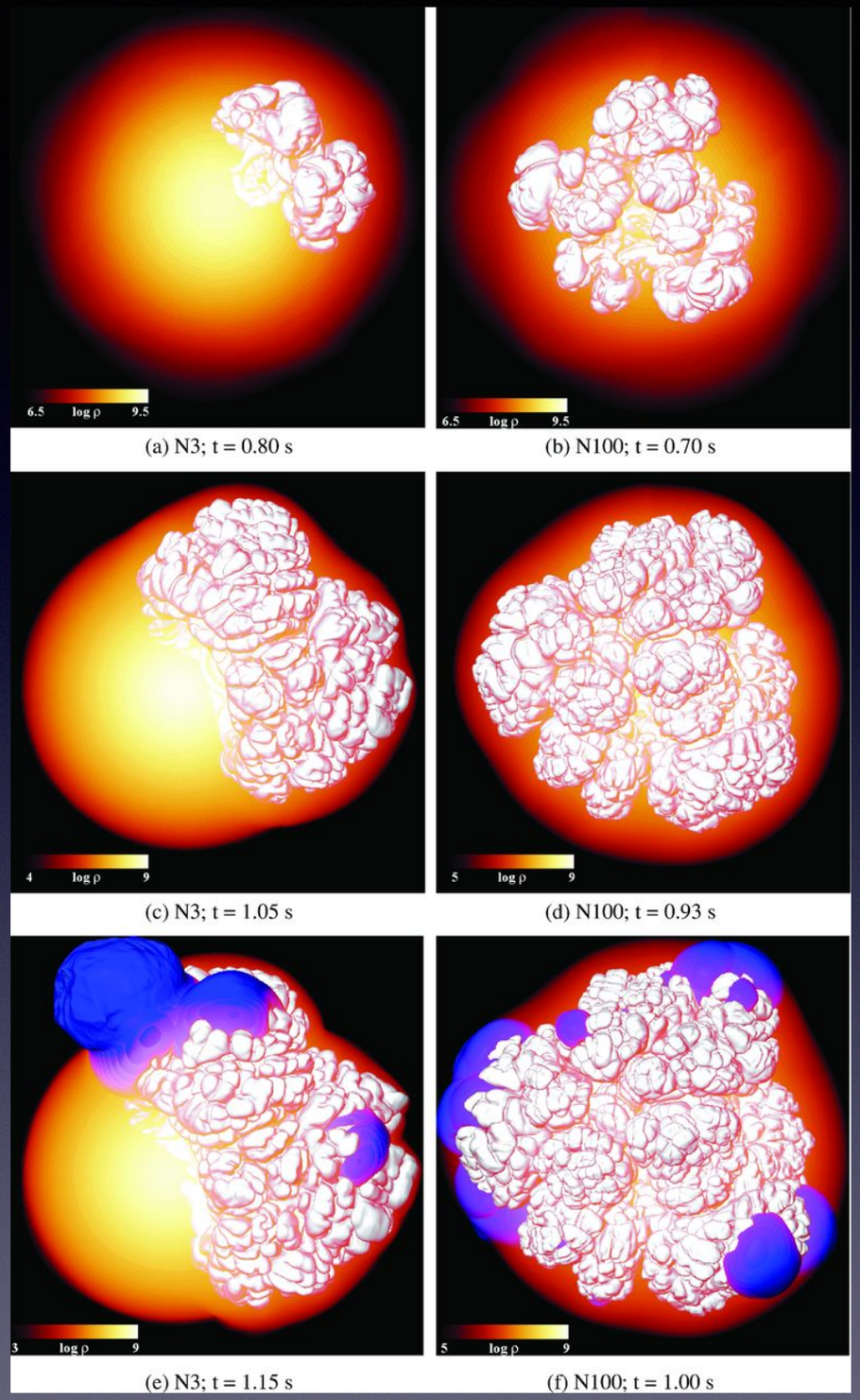
X,Y: Proper motions from 2003/2015 Chandra images
Z: Doppler shift of Si and S lines in Chandra spectra



Note: apparent “flattening” is illusion caused by lack of data down the center of the remnant, but see Sato & Hughes 2017

N3 Model
Fewer detonation points
Less symmetry

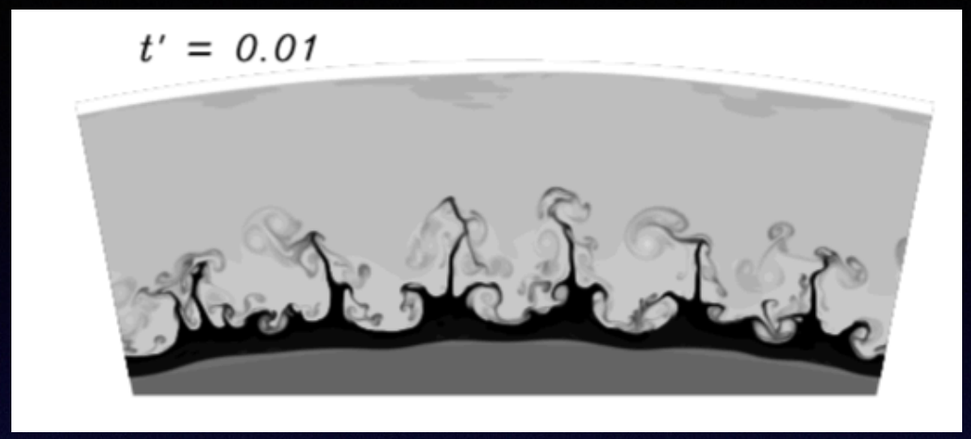
Models from Seitenzahl+ (2013)



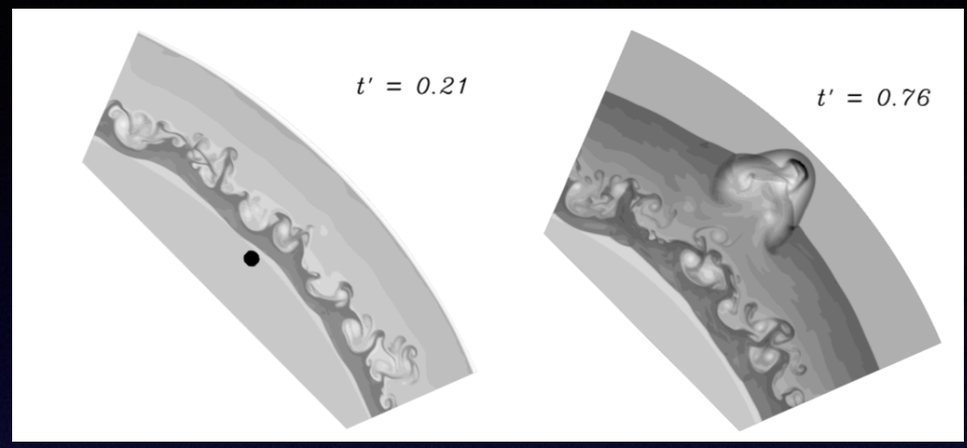
N100 Model
More detonation points
More symmetry

Tycho appears more consistent with symmetric expansion, perhaps implying more detonation points within the WD. LOTS of caveats here (possible selection biases, only Si ejecta used, substantial error bars, etc.)

Constraint on initial density profiles?

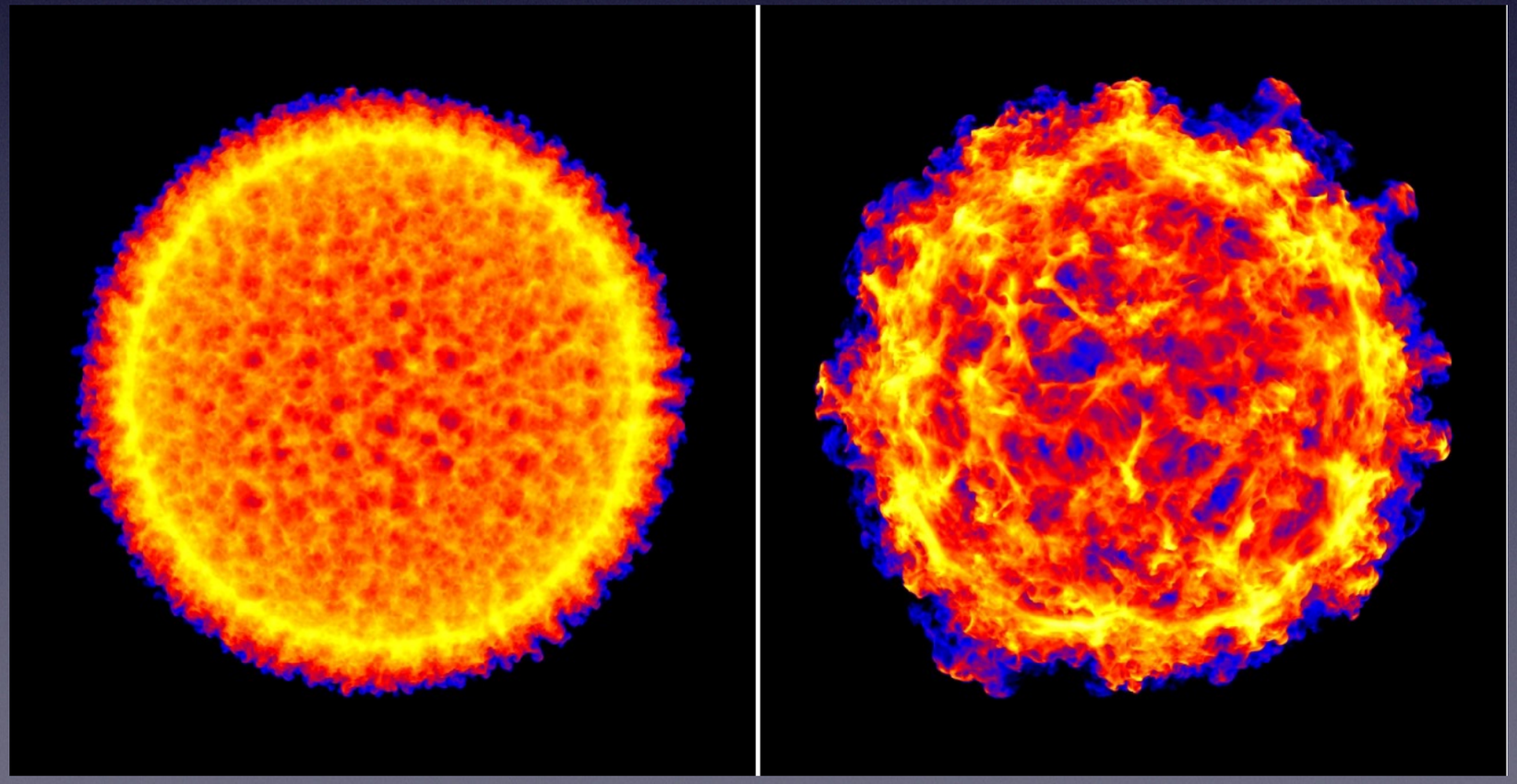


2D simulations from
Wang & Chevalier (2001)

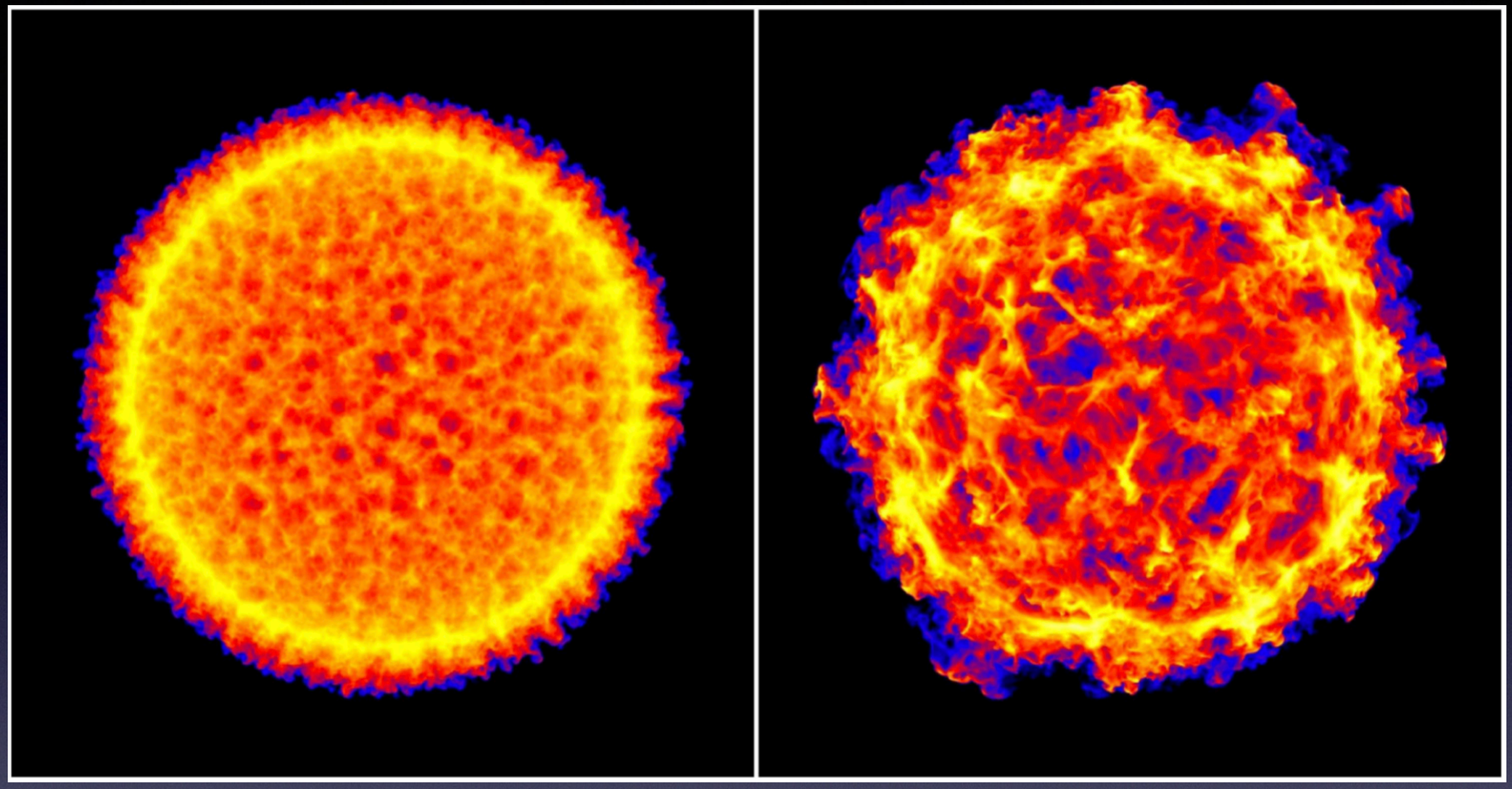


Smooth initial ejecta, structures due to Rayleigh-Taylor instabilities

Structures due to initial clumps (56Ni bubble?)



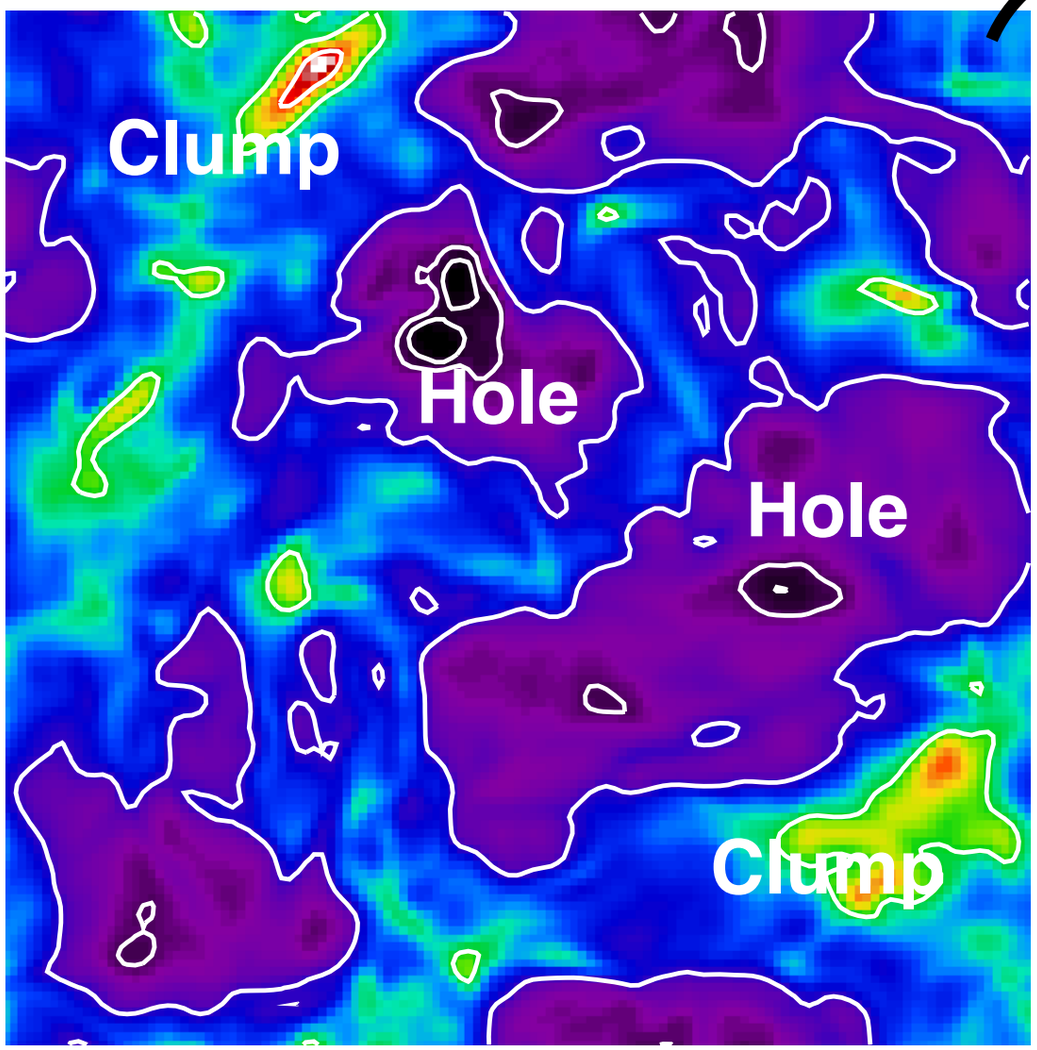
3D simulations of smooth and clumpy ejecta models at age of Tycho

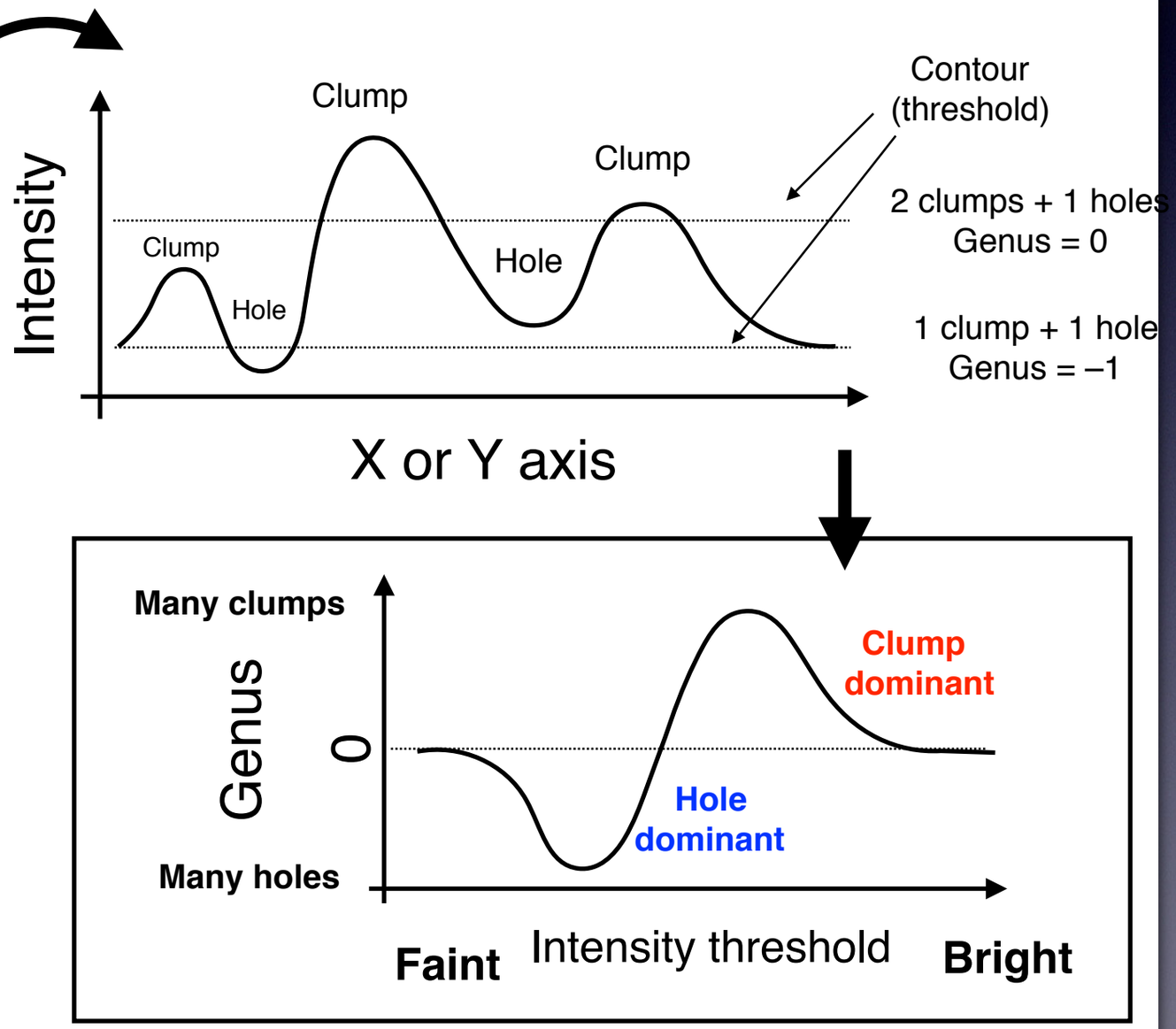


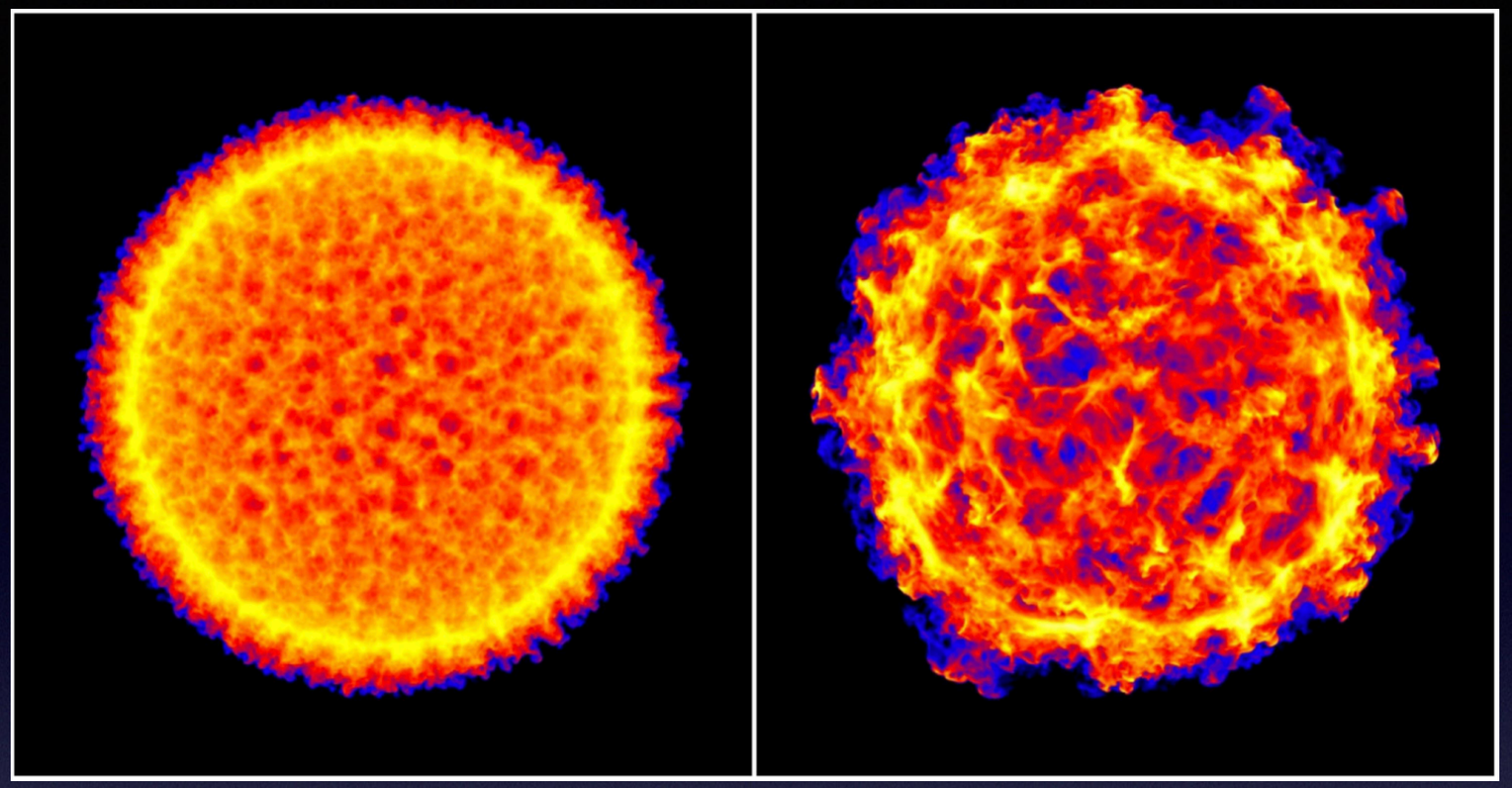
The kinematics of two models are very similar, but they just *look* much different…

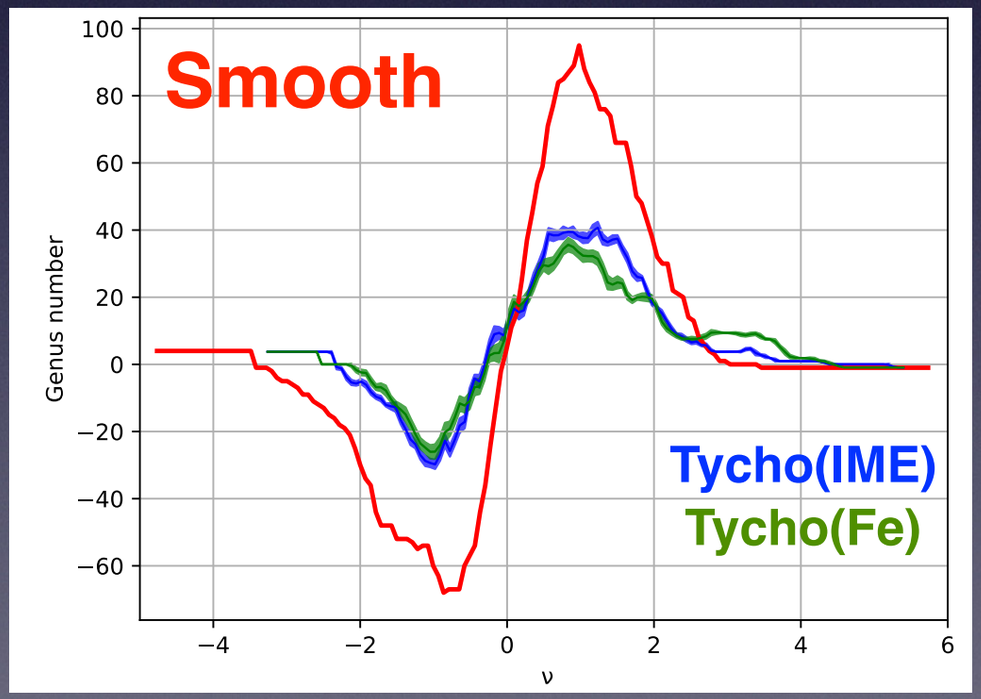
Enter: "Genus statistics" method. Work done by my collaborators Mikio Morii (ISM/Tokyo), Toshiki Sato (RIKEN/GSFC)

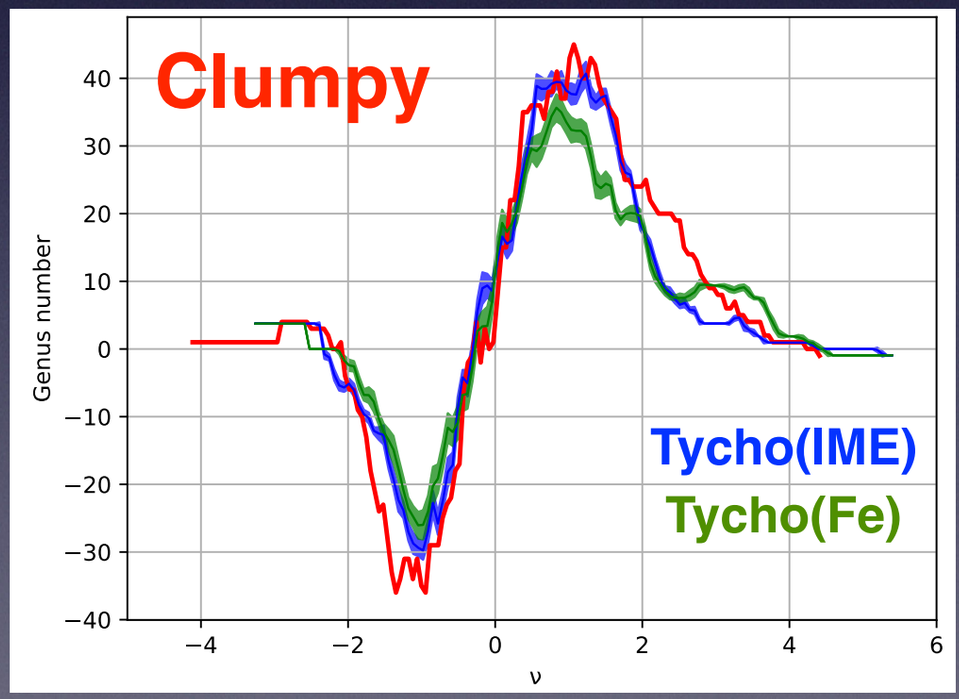
- A method to analyze topology of the large-scale structure of the cosmos
- Calculate the Homology (count the number of holes and clumps) at each contour











The genus statistic strongly supports an initial clumped ejecta distribution as the origin of the clumps in Tycho's supernova remnant. See Sato et al. (2019)

Summary and Closing Thoughts

- Tycho appears to be the result of a normal Type Ia SN interacting with inhomogeneous ISM
- Expansion velocities of forward shock vary by 50%, range from ~4,000 to 6,000 km/s
- Kinematics of ejecta favor WD that exploded with many ignition points, symmetrical expansion, clumpy ejecta distribution

- With all the cool things happening in multi-wavelength and multi-messenger astronomy, don't forget about *multi-epoch astronomy*
- How can we best leverage 20 years of Chandra legacy to make progress? What would we regret not doing?
- When the next generation of observatories come online, need to think about what to do early on that will pay off later…